Foraminiferal record and astronomical cycles: An example from the Messinian pre-evaporitic Gello Composite Section (Tuscany, Italy)

Foraminiferal record and astronomical cycles: An example from the Messinian pre-evaporitic Gello Composite Section (Tuscany, Italy)

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ABSTRACT: A high resolution bio-magneto and cyclostratigraphical study has been carried out for the first time on Messinian pre-evaporitic marine deposits (Gello Composite Section) from the Volterra Basin (Italy). Since the investigated deposits manifest no evident lithological cyclicity, others records have been used to recognize the evidences of an astronomical periodicity. The distribution curves of planktonic and benthic foraminifera have been used for paleoenvironmental reconstruction. Cyclostratigraphical analyses have been based on: i) abundance fluctuations of Bolivina and Bulimina among the benthic foraminifera, Globigerinoides, Orbulina and Turborotalita among the planktonics; ii) $CaCO_3$ content changes; and iii) Shannon-Weaver index variations relative to benthic assemblages. As a result, 18 precession-controlled cycles have been recognized. Moreover, the recognition of the C3An.1r, C3An.1n and C3r magnetozone and some bio-chronohorizons, have allowed the tuning of the studied section with the ATNTS (Astronomical Tuned Neogene Time Scale) using the Laskar 2001 (1,1.2) solution of the insolation curve. This multidisciplinary study strongly supports that the onset of evaporitic deposition in Tuscany and in other circum-Mediterranean type-successions, as the Abad Composite Section (Spain) and the Falconara Section (Sicily), was isochronous.

INTRODUCTION

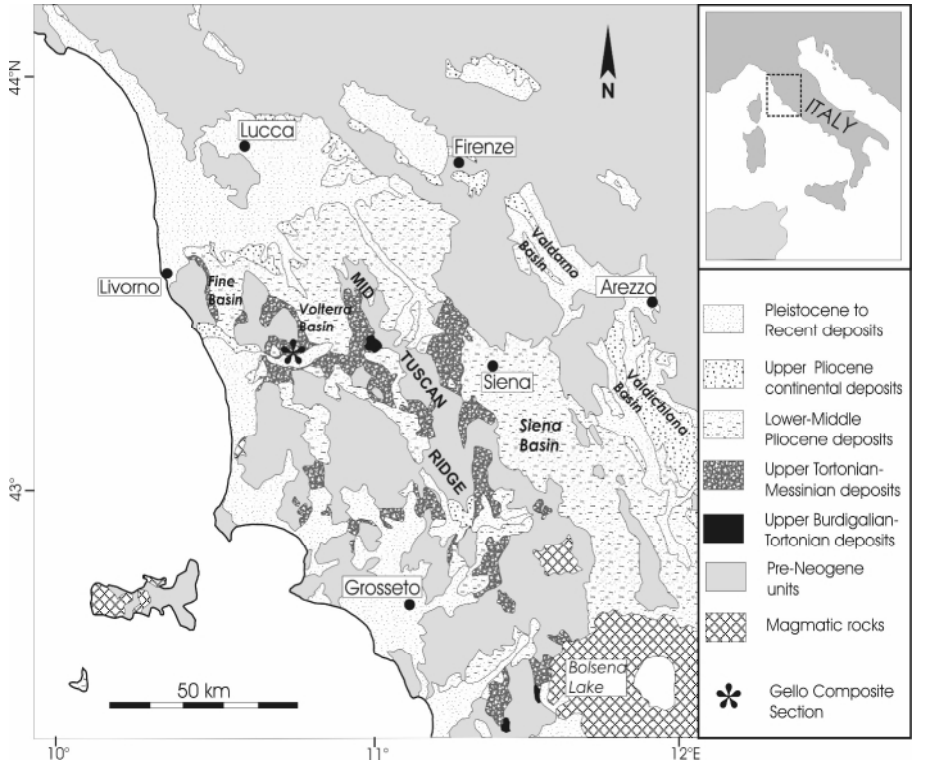
In the Mediterranean area, the early Messinian culminated in a regional evaporitic phase marked by the deposition of peculiar facies, mainly represented by anoxic sediments, carbonates and sulphates. The beginning of primary evaporitic deposition is still a matter of debate. In fact, whereas it has been traditionally considered as an isochronous event, as documented by several astronomically calibrated sections (e.g. Sprovieri et al. 1996b,

Hilgen and Krijgsman 1999, Krijgsman et al. 1999, Sierro et al. 2001, Krijgsman et al. 2004), some authors have recently supposed that it initially occurred in marginal areas contemporarily with deposition of anoxic clays in the deeper part of the basins (Roveri et al. 2001, Roveri et al. 2003). The Messinian evaporitic phase is recorded in the western Neogene Tuscan basins, which manifest remarkable variations in sedimentation patterns and paleobiogeography resulting from the complex interplay between regional and global factors. Specifically, the lower Messinian marine areas in Tuscany were characterized by shelf to coastal basins affected by evaporites deposition considered biostratigraphically time equivalent with that of others Mediterranean areas (Bossio et al. 1996 and references therein). Nevertheless, no magnetostratigraphic or high resolution biochronological/ cyclostratigraphical data support this inference.

During the last decade cyclostratigraphy based on lithological cycles (Hilgen 1991, Hilgen et al. 1995, Hilgen et al. 2003 and reference therein) or relative abundance fluctuations in the planktonic assemblages (Sprovieri 1992, Sprovieri 1993, Sprovieri et al. 1996a, Sprovieri et al. 1996b) and astrochronological calibration, have become new tools for the construction of a high resolution stratigraphy. The classic high frequency cyclicity recognized in most of the late Neogene Mediterranean record is manifested by the alternation of homogeneous marls and sapropel (or sapropel equivalent) horizons, with sapropels deposition promoted by astronomical forcing (Hilgen et al. 1995). In this framework, since Messinian pre-evaporitic marine deposits of Tuscany do not show rhythmic lithological patterns, cyclostratigraphy and astronomical tuning to the ATNTS (Astronomical Tuned Neogene Time Scale) (Lourens et al. 2004), has been carried out by means of foraminifera-based proxies (e.g. Caruso 2004).

The Gello Composite Section is characterized by oligotypic foraminiferal assemblages with benthos dominated by buliminids or bolivinids, and plankton mainly constituted by orbulinids or turborotalitids. The abundance fluctuations of these taxa have been induced by astronomical periodicity both in Plio-Pleistocene sapropel cyclical deposits (e.g. Cita and Podenzani 1980, Ross and Kennett 1983/1984, Katz and Thunell 1984, Rio et al. 1997) and in Messinian pre-evaporitic sequences (Sprovieri 1992, Sprovieri 1993, Sprovieri et al. 1996a, Sprovieri et al. 1996b, Sprovieri et al. 1999, Sierro et al. 1999, Vazquez et al. 2000, Bellanca et al. 2001, Sierro et al. 2001, Blanc-Valleron et al. 2002, Pérez-Folgado et al. 2003, Sierro et al. 2003). Therefore, evidence of an astronomical periodicity has been based on the distribution curves of these taxa together with others climatic/environmental sensitive records, such as specific diversity index, $CaCO_3$ content and magnetic susceptibility.

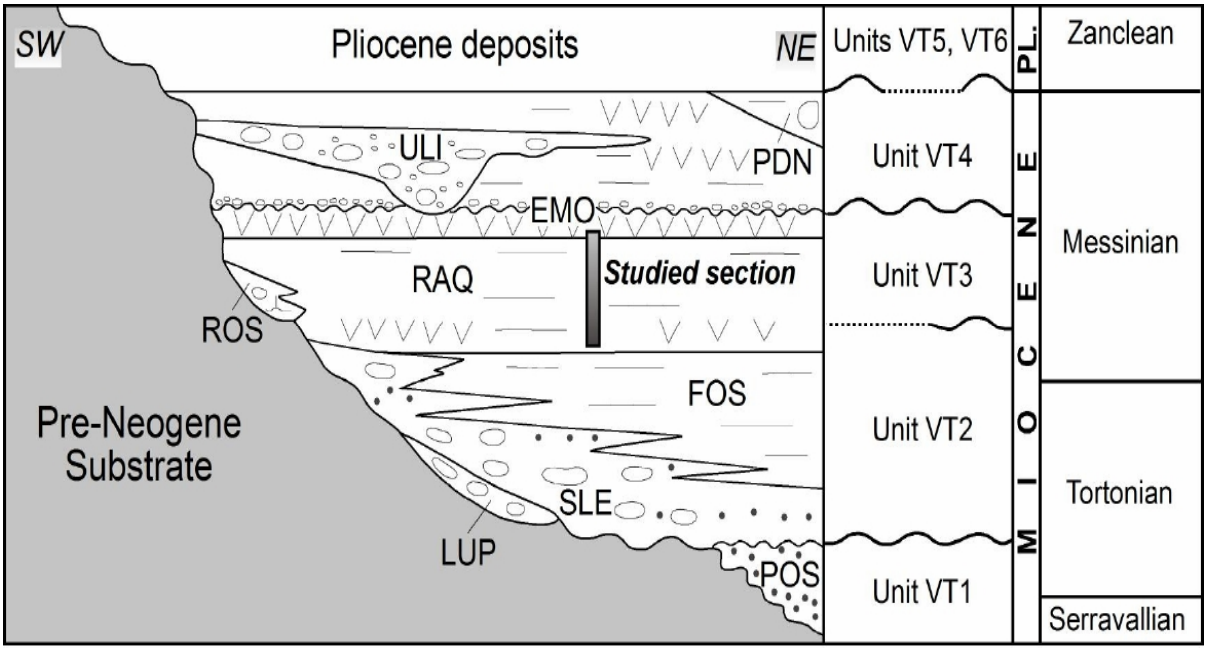
GEOLOGICAL SETTING



Text-figure 1 - Simplified geological map of the inner Northern Apennines with location of the studied

The Volterra Basin (text-fig. 1) is a 15Km-wide and 60Km-long morpho-structural depression formed in inner side (western Tuscany) of Northern Apennines starting from the Miocene (Martini et al. 2001 and references therein). The bedrock consists of thrust-faulted and folded, Triassic to Oligocene carbonates, sandstones, ophiolites and cherts (Ligurid and Tuscan units). The structural origin of this basin is related to an extensional tectonics which acted since Middle Miocene (Bossio et al. 1998, Pascucci et al. 1999, Sandrelli 2001 and references therein), although some Authors interpret the tectono-sedimentary evolution of the Volterra Basin as developed in a compressive setting (Bonini and Moratti 1995, Cerrina Feroni et al. 2006).

The Volterra Basin is filled with about 2500m of Neogene-Quaternary deposits grouped into six main (VT1-VT6) allounits (text-fig. 2) (Bossio et al. 1997, Sandrelli 2001, Pascucci et al. 2004). Unit VT1 (Ponsano Sandstone, POS) comprises Serravallian-lower Tortonian shallow marine sandstones with occasional marls. Unit VT2 is upper Tortonian-early Messinian in age and consists of fluvial conglomerates (Luppiano Conglomerates, LUP) overlain by alluvial fan conglomerates and sandstones (Sellate Fm, SLE) grading upward and basinward to freshwater and brackish clays (Fosci Creek Fm, FOS), which are in turn overlain by alternating gypsum and marly beds (lower part of the Raquese Creek Fm, RAQ). Unit VT3 includes early Messinian conglomerates and reefal limestones (Rosignano Limestones, ROS), passing upward and basinward to Pycnodonta-bearing clays (upper part of the Raquese Creek Fm, RAQ). These are overlain by alternating primary gypsum



Text-figure 2 - Sketch of the Miocene lithostratigraphic and allostratigraphic units exposed in the Volterra Basin (modified after Sandrelli 2001, see text for explanation).

and clays (lower part of the Era Morta River clays and gypsum, EMO), which record the evaporitic phase of the Messinian Salinity Crisis in the Volterra Basin. A basin-wide unconformity surface separates unit VT3 from the overlying unit VT4, related to the post-evaporitic phase (Lago-mare l.s.). Unit VT4 comprises local conglomeratic bodies (Ulignano Conglomerate, ULI; and Podernuovo Conglomerate, PDN) and dominantly clays with minor conglomerates, sands, gypsarenites and gypsorudites (upper part of the Era Morta River clays and gypsum). An Early Pliocene marine transgression related to the refilling of the Mediterranean area marks the end of the Lago-mare sedimentation. Units VT5 and VT6 comprise variously associated Lower to Middle Pliocene clays, sands, conglomerates and biocalcarenites. On the western side of the basin, close to the studied sections, minor lamproite intrusions emplaced during the Early Pliocene (Innocenti et al. 1992).

OBJECTIVES AND METHODS

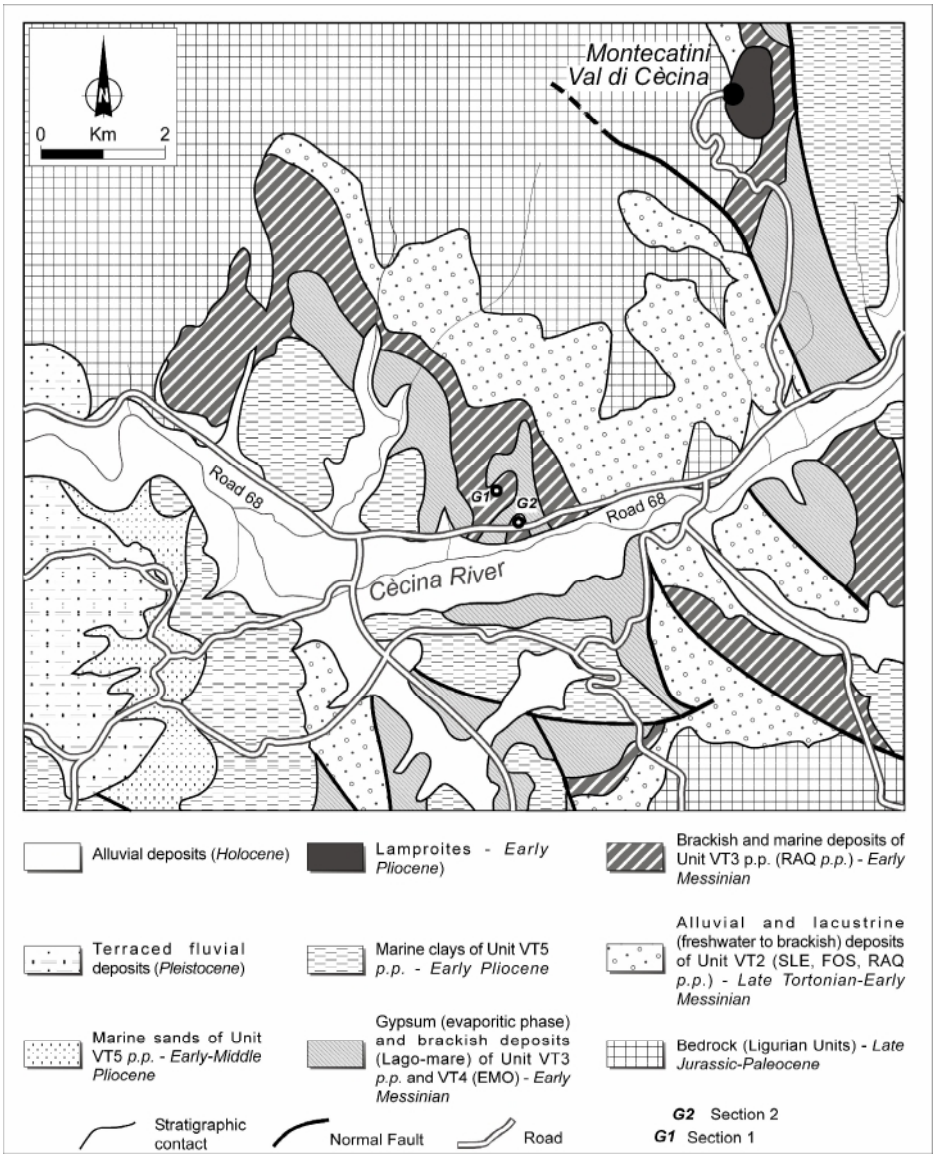
Main goal of this paper is to define times and modes of the early Messinian sedimentary history of the Volterra Basin, with emphasis on the beginning of the evaporitic phase as revealed by cyclostratigraphic and astrochronological studies focused on the upper part of the Raquese Creek Fm (Gello Section) in its best exposure area (Gello locality). According to previous Authors (Bossio et al. 1996 and reference therein), this unit has been attributed

to the Non Distinctive Zone, sensu Iaccarino and Salvatorini (1982) (the sinistral/dextral coiling change of Neogloboquadrina acostaensis is the marker of the base of the Zone) and is thought to be deposited in the early Messinian.

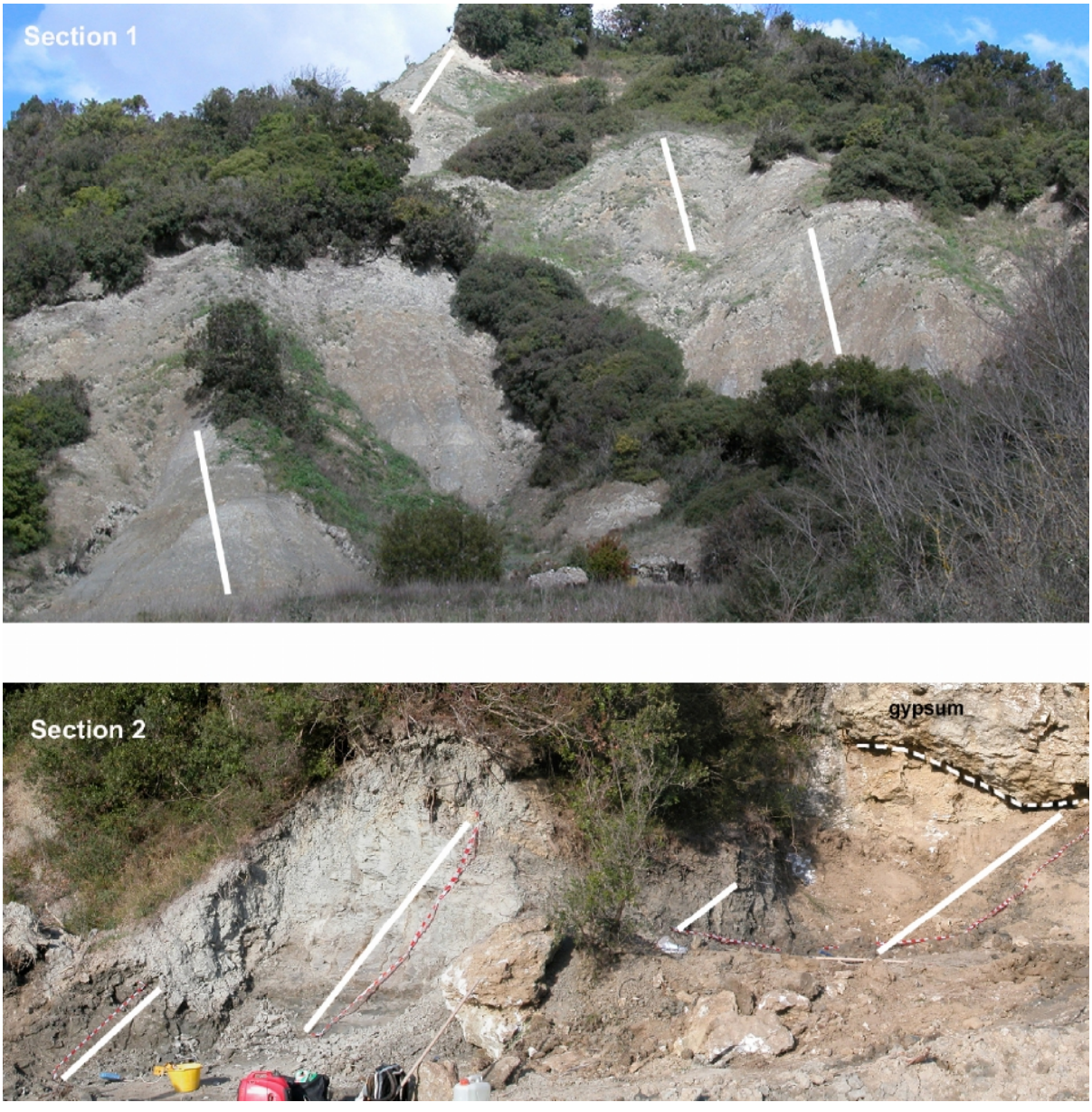
The pre-evaporitic Gello Section is about 60m thick and comprises two parts (hereafter Gello Composite Section). The lower part (hereafter Section 1, about 50m thick) is located in a badlands area, few hundreds meters far from Road 68, whereas the upper one (hereafter Section 2, about 10m thick) crops out along the above mentioned road (text-fig. 3).

The Gello Section 1 (text-figs. 4-5) comprises dominantly massive grey marly clays and marls with intervening thinly-laminated marly clays (<2m) and a sandy gravel bed (max 30cm) in the lower and middle part of the section, respectively.

The Gello Section 2 (text-figs. 4-5) consists of about 10m thick massive marly clays with in its middle part a 10cm thick layer bearing rod-shaped, centimetre-sized corals which are



Text-figure 3 Schematic geological map of the surroundings of Gello locality (modified after Carmignani and Lazzarotto, 2004).

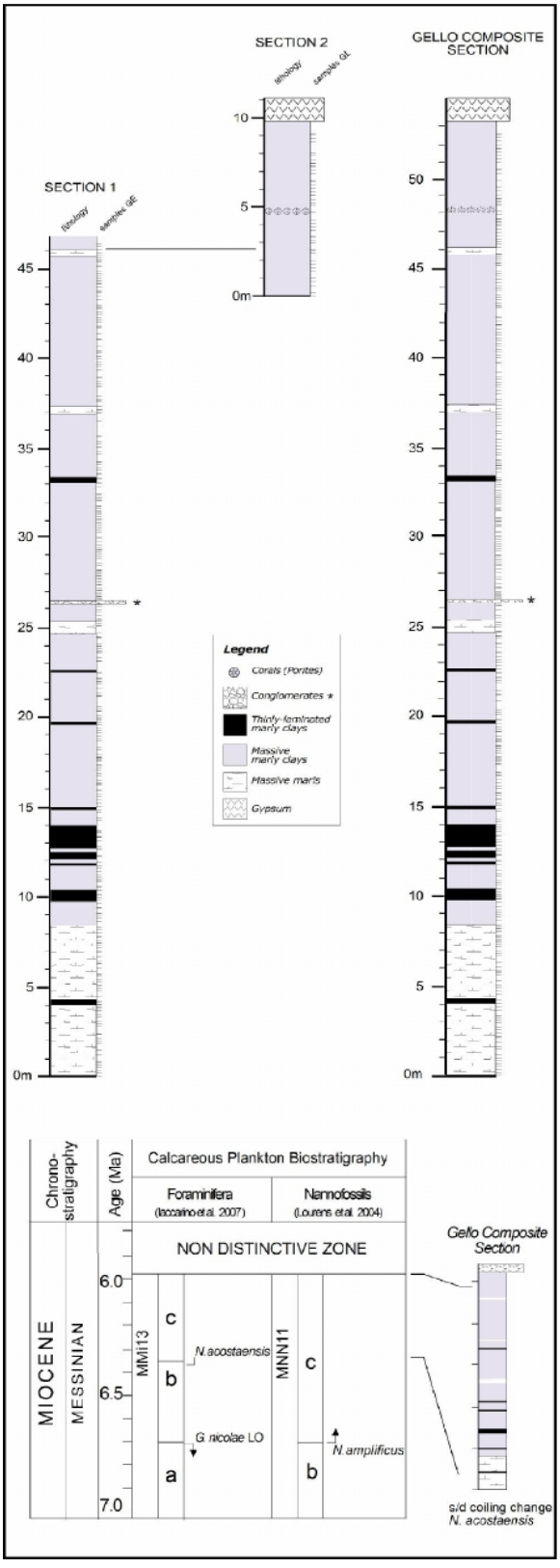


Text-figure 4
Panoramic view of the studied sections. White bars indicate the sample trajectories.

not in life position. It ends with a few meters of alabastrine gypsum, whose correlative gypsum exposed elsewhere in the basin consists of selenite and records the evaporitic phase of the Messinian Salinity Crisis.

About 400 samples, with an average spacing of 15cm, have been cored along the succession and characterized in terms of micropaleontological, sedimentological, carbonate content and geophysical (magnetic susceptibility, paleomagnetic analyses) features.

The analysis of both planktonic and benthic foraminifera associations has been tested in order to recognize evidence of an astronomically induced cyclicity. To this purpose, the

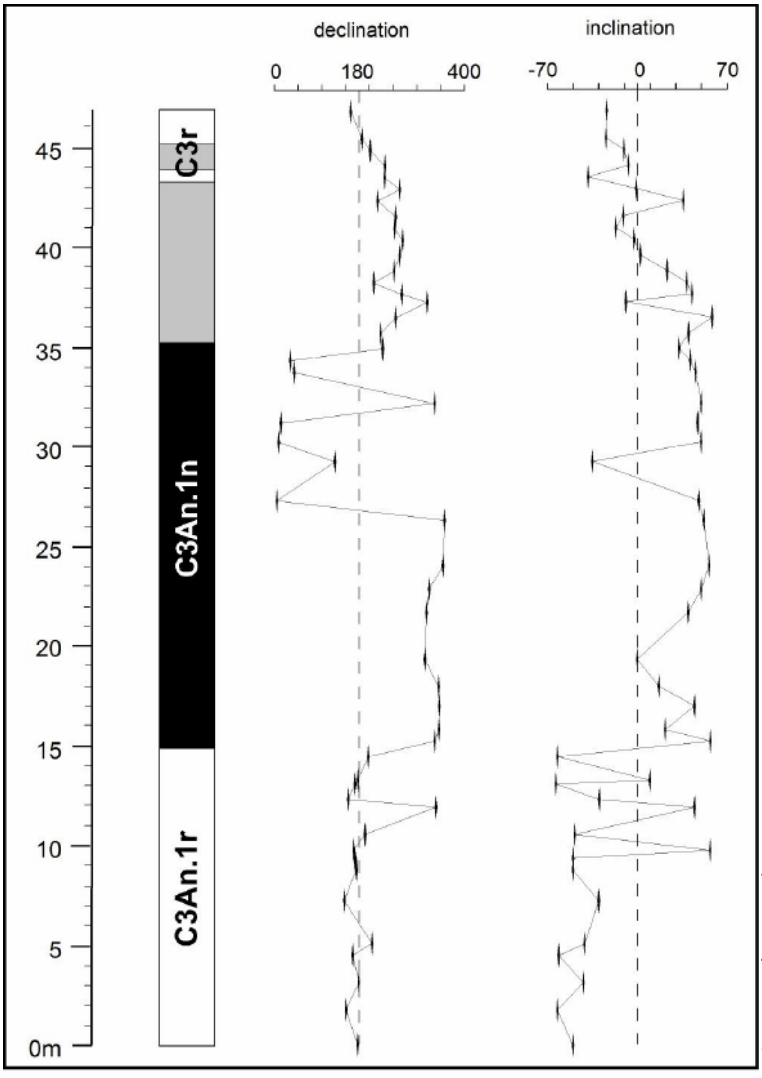


Text-figure 5 Stratigraphic columns of Section 1 and Section 2 forming Gello Composite Section framed in the biostratigraphic scheme (see text for correlation criteria).

study section has been partitioned in paleoenvironmentally and paleoecologically homogeneous intervals, each one characterized by its own paleoenvironmentally controlled cyclostratigraphic proxies.

MAGNETOSTRATIGRAPHY

Magnetostratigraphic analyses were performed at the Peveragno Paleomagnetic Laboratories (ALP), where the natural remnant demagnetisation of 50 samples was measured on a 2G ENTERPRISES DC-SQUID cryogenic magnetometer. Samples were thermally demagnetised throughout 30°C increments, up to a maximum of 440°C, even if most of the samples showed low intensity of magnetisation or random directions of the field yet at 400°C. NRM intensities vary from low values (0.035mA/m) to a maximum of 4.92mA/m, but most of them are comprised between 0.3 and 0.7 mA/m. The results were corrected for bedding and core sample orientation, then the principal component analysis (PCA) was performed on the Zijderveld diagrams to reconstruct declination and inclination directions. The analysis revealed (text-fig. 6) the presence of two components: a low temperature (0°-210°C) normally directed component and a high temperature (210°-420°C) normal or reverse component. This high temperature component is thought to be the characteristic remanent magnetisation (ChRM), while the low temperature

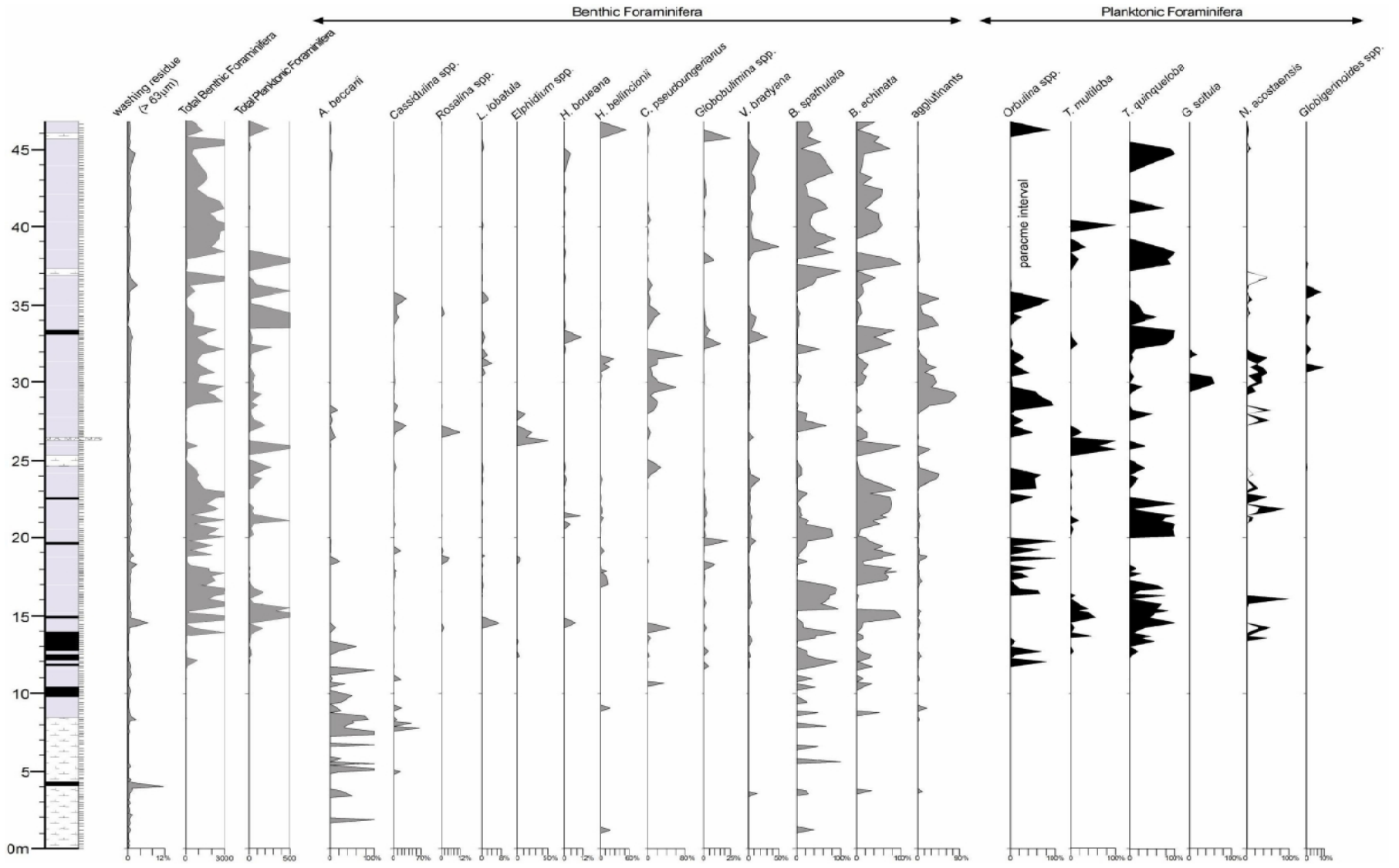


Text-figure 6
Magnetostratigraphic data from Section 1. In the polarity column, grey intervals represent unreliable results.

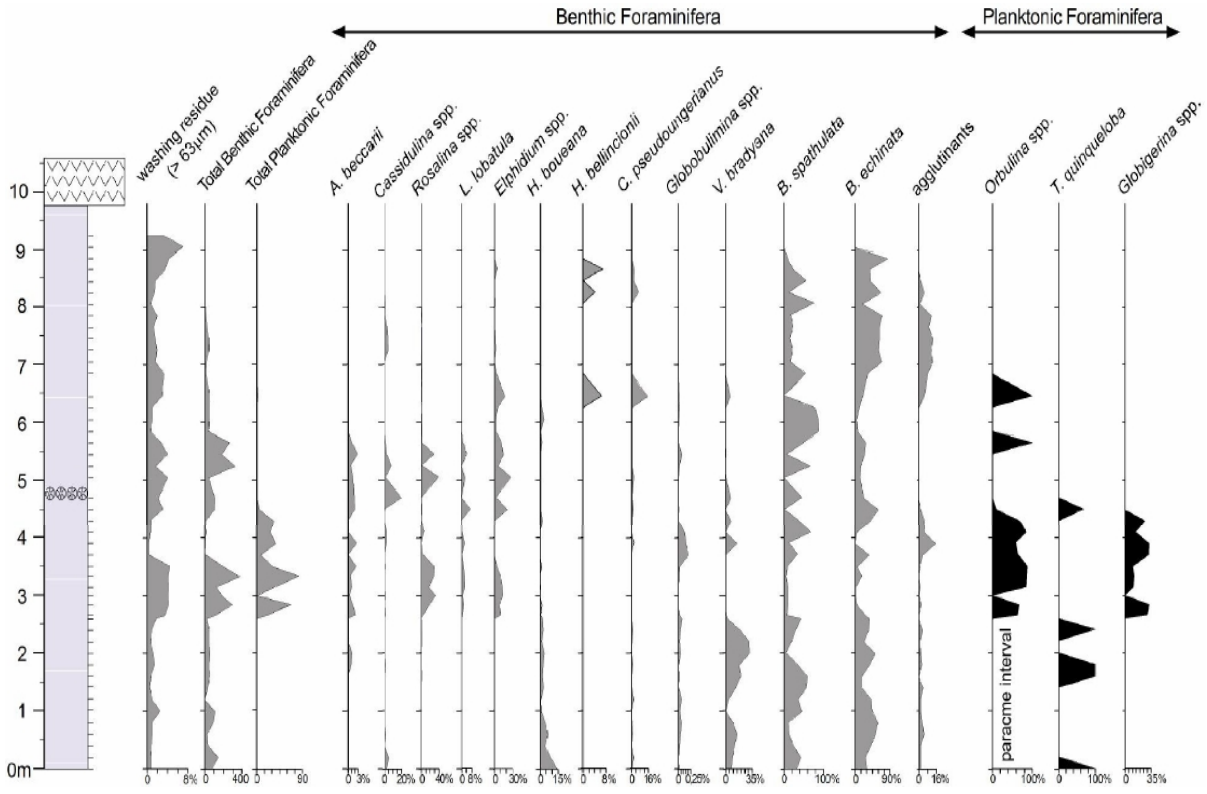
component, always of normal polarity, is interpreted as the present day field. In the lowermost part of the section up to 35m data are much clearer, consequentely a R/N reversal boundary is individuated at 14.77m, which is interpreted as the boundary between the C3An.1r and C3An.1n magnetic intervals. From 35m upward an undetermined interval is present, preventing the individuation of the top of the C3An.1n subchron. Nevertheless, the presence of clearly reversal polarity samples at 43.47m and at the top of the sampled interval, allow the identification of C3r magnetochron.

MICROPALEONTOLOGICAL DATA

Micropaleontological analyses have been performed on the foraminifer (179 samples) and calcareous nannofossil (47 samples) assemblages from Section 1 (text-fig. 7) and Section 2 (text-fig. 8). In particular, foraminifer assemblages have been analysed with a quantitative method, whereas a semiquantitative method has been used for nannofossils.



Text-figure 7 Quantitative distribution of selected foraminiferal taxa within Section 1. White colour in Neogloboquadrina acostaensis distribution indicates the percentage of sinistral forms.



Text-figure 8 Quantitative distribution of selected foraminiferal taxa within Section 2.

Nannofossil smear slides have been prepared with traditional techniques. As regards the foraminifera, 100g of sediment from each sample has been disaggregated in normal water and washed on 63μm sieve. After washing, samples have been splitted with a microsplitter and at least 300 specimens of planktonic as well as benthic specimens have been counted in the >125μm dry fraction.

Furthermore, the diversity of benthic foraminifera has been calculated and expressed by the Shannon-Weaver and Fisher alpha indices (Murray 1991). The planktonic/benthic ratio of the counted foraminifera has been expressed as %P=100 x [P/(P+B)] (e.g. Van der Zwaan et al. 1990, Kouwenhoven et al. 2006). Finally, valves and fragments of Ostracod have been also counted for each sample.

Correlation of the sections

Section 1 and Section 2 cannot be lithologically correlated. The marly horizon at the top of Section 1 is not present in Section 2, which, in turn, contains a 15cm-thick layer bearing Porites in horizontal position not present in Section 1 (text-fig. 5). Since such lithofacies likely represent local feature, reliable correlation elements between sections 1 and 2 are based on abundance distribution patterns of some foraminifera taxa (text-fig. 7-8). Specifically, the upper part of Section 1, from 35.85m (sample GE 260) to 46.25m (sample

GE 325), is characterized by a paracme interval of orbulinids. In the uppermost part of this interval, a distinctive peak in abundance of Turborotalita quinqueloba closely predates the reappearance of the orbulinids. Moreover, in the orbulinid paracme interval, Bulimina echinata, Bolivina spathulata and Valvulineria bradyana show high frequencies, whereas agglutinants are practically absent. The same distribution characterizes the base of Section 2, where the paracme of orbulinids ends at 2.65m (sample GL 15). Above the paracme, orbulinids are abundant and it is possible to correlate their reappearance to the base of the "orbulinites" level, as defined by Sprovieri et al. (1996a). Consequently, considering the sample levels GE 325 (46.25m) and GL 15 (2.65m) as time equivalent, Section 1 and Section 2 can be joined to form the Gello Composite Section (text-fig. 5-9).

Benthic foraminifera

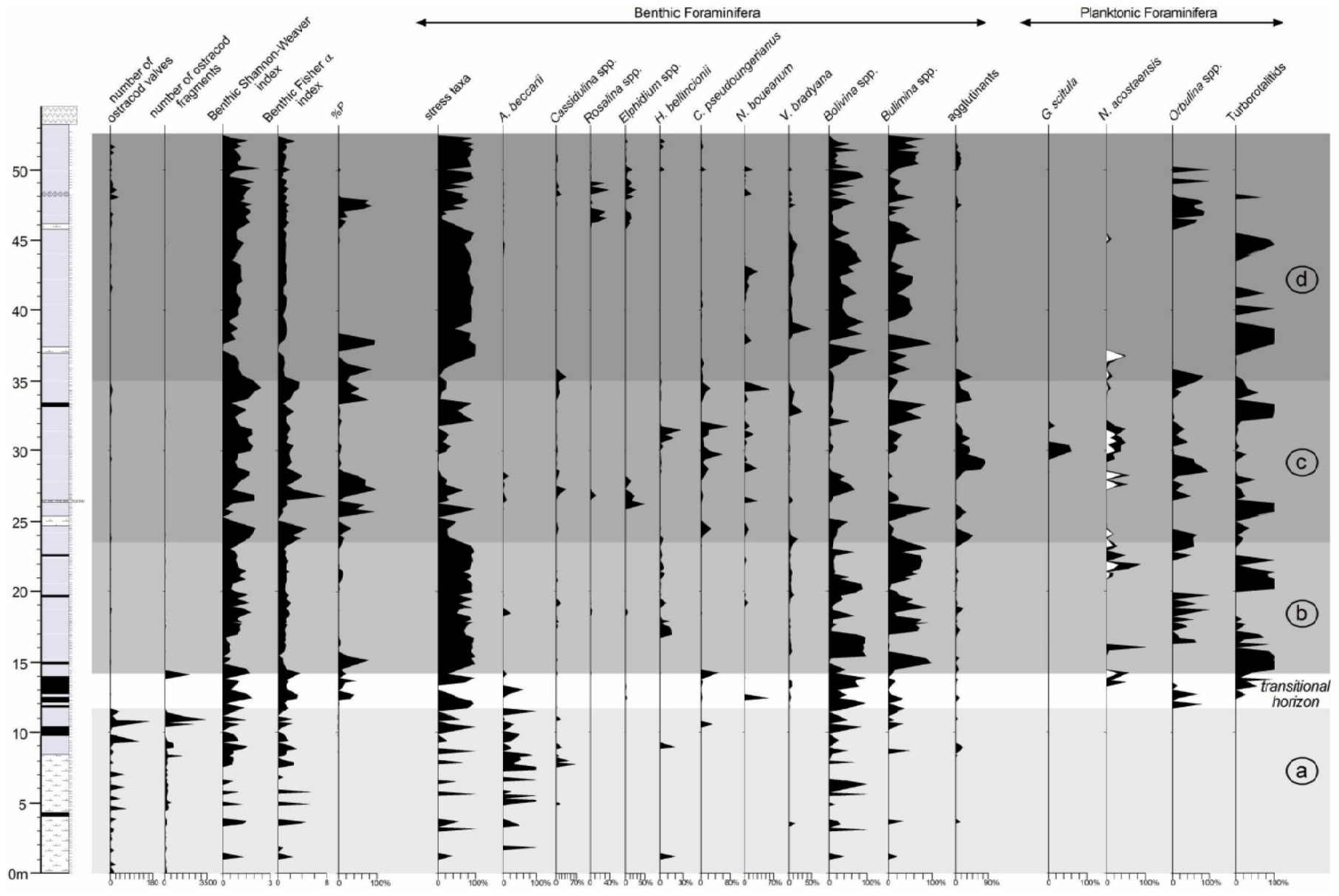
Benthic foraminifera are present throughout the whole Gello Composite Section and show high frequencies and good preservation. The distribution of dominant, common or significant species is reported in text-figure 9; their abundance is expressed as percentage of the total assemblage.

The most representative species of the diverse benthic foraminiferal fauna are bolivinids (Bolivina. antiqua, B. arta, B. dentellata, B. dilatata, B. plicatella mera, B. spathulata), bulimininids (B. buchiana calabra, B. costata, B. echinata, B. elongata, B. inflata, B. minima) and Ammonia beccarii. Additional and significant taxa are elphidiids (Elphidium. aculeatum, E. advenum, E. complanatum, E. crispum, E. macellum, Prothelphidium granosum), Cibicidoides pseudoungerianus, Heterolepa bellincionii, Cassidulina spp., Globobulimina spp. (G. affinis, G. ovula, G. pyrula), V. bradyana and agglutinants (text-figs. 7-8).

Bolivinidae and Buliminidae dominating throughout the succession, strongly fluctuating in the range of 0.3-100% and 0.1-99%, respectively.

Among the bolivinids, B. spathulata and B. dentellata are the most common. B. spathulata is present from the base of the Gello Composite Section, displaying peaks of abundance around 30-40%. Upward from 10m, this species shows a continuous distribution with highest frequencies in the range of 0.3-100%. B. dentellata is present with highest abundance in the intervals 14-25m and 32-45.5m in the range of 1-64% and 1-47%, respectively. Bolivina dilatata, occur in the lower and middle part of the section and shows low frequencies (max 10%). The abundance patterns of B. spathulata and B. dilatata are key elements for paleoenvironmental reconstruction, because they are mud-dwellers with tolerance for oxygen depletion and preference for high nutrient condition, with the latter less tolerant to high salinity than B. spathulata (Van der Zwaan 1982).

Concerning the buliminids, B. echinata is the dominant species, which is known to


Benthic Foraminifera
Planktonic Foraminifera
number of ostracod valves
number of ostracod fragments
Benthic Shannon-Weaver index
Benthic Fisher α index
%P
stress taxa
A. beccarii
Cassidulina spp.
Rosalina spp.
Elphidium spp.
H. bellincionii
C. pseudoungerianus
N. boueanum
V. bradyana
Bolivina spp.
Bulimina spp.
agglutinants
G. scitula
N. acostaensis
Orbulina spp.
Turborotalitids
50
45
40
35
30
25
20
15
10
5
0m
d
c
b
a
transitional horizon

characterize marine pre-evaporitic Messinian marls (Colalongo et al. 1979) being tolerant to high environmental stress, especially low oxygen content. It occurs in the basal part of the succession with frequencies at 33-50%, from 10m upward it shows a continuous distribution with great number of individuals in the range of 0.1-99.3%.
Ammonia beccarii (with tepida form) is commonly present with high frequencies (90%) only in the lower part of the section.
Some taxa, as Asterigerinata planorbis, Elphidium spp., Cassidulina spp., Cibicidoides pseudoungerianus, Globobulimina spp., Heterolepa bellincionii, Melonis soldanii, Nonion boueanum and Valvulineria bradyana, are increasing in the interval between 24m and 35m. Moreover, in the topmost part of the section V. bradyana, Rosalina spp. (R. brady, R. floridana) and Elphidium spp. show peaks of abundance around 30%. All these taxa have a great tolerance to increased salinities and, among them, C. pseudoungerianus and Hanzawaia boueana are not tolerant to oxygen deficiency (Van der Zwaan 1982).
Finally, agglutinated foraminifera (Dorothia sp., Glomospira sp., Haplophragmoides spp., Martinottiella communis, Textularia spp., Reophax spp.) are rare except for three peaks of abundance (45-85%) in the interval between 25m and 35m. The absence or scarcity of these species is known to be peculiar of Messinian deposits (Goubert et al. 2001).

Planktonic foraminifera

The distribution of planktonic foraminifera, locally poorly preserved, is discontinuous along the Gello Composite Section. Particularly, the assemblages are absent in the lower part of the section, moderately well preserved and diversified in the middle one, whereas they show a gradual decrease in diversity in the upper part. Trend of selected taxa are plotted in text-figure 9, with taxon abundance expressed as percentage of the total assemblage.
The most representative taxa are T. quinqueloba and Orbulina spp. (O. bilobata, O. suturalis, O. universa). Additional and significant taxa are Globigerinoides spp. (G. cf. elongatus, G. extremus, G. obliquus), Neogloboquadrina acostaensis, Turborotalita multiloba and Globorotalia scitula (text-figs. 7-8).
T. quinqueloba, known as a superficial cool species, common in nutrient-rich waters and tolerant to hypersaline conditions (Kroon et al. 1988, Van de Poel 1992), occurs firstly at 12.42m from the base and is present discontinuously until 48m with high abundance (0.1-

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Text-figure 9 Cartoon showing the main features of the Gello Composite Section: distribution of selected foraminifera taxa; diversity index (Shannon-Weaver and Fisher alpha); percentage of planktonic foraminifera expressed as %P = planktonic/planktonic+benthic X 100; relative abundance of ostracods expressed as number of entire valves (entire carapace counted as 2) and fragments; stress taxa = total percentage of buliminids + bolivinids. White colour in Neogloboquadrina acostaensis distribution indicates the percentage of sinistral forms. Intervals A, B, C and D (represented by different grey tones) correspond to the diverse paleoenvironmental settings (see text for explanation) recorded by the investigated section.

100%).
Orbulina spp., thriving in relatively warm and oligotrophic surface waters and common to dominant in the Messinian pre-Salinity Crisis assemblages (Sprovieri et al. 1996a, Sprovieri et al. 1996b, Blanc-Valleron et al. 2002, Sierro et al. 2003, Kouvenhoven et al. 2006), first occurs at 12.07m. It shows high frequencies and decreases from about 35m, manifesting a paracme interval up to 46.40m; from this to 50m orbulinids are common with a peak of abundance of 90%.
T. multiloba shows an apparent random distribution, it appears at 12.72m with low percentage value (6.25%), following peaks of abundance in the interval 13.7-16m, at 25m and 38m in the range of 1.8-55.3%, 99% and 33%, respectively. This form, considered by some authors as an ecophenotipic species related to the progressive Messinian isolation of the Mediterranean Sea (e.g. Sierro et al. 2003), is a cold, eutrophic water species which may be well tolerant to increasing salinity.
Globigerinoides spp., indicative of warm subtropical superficial waters (Sprovieri et al. 1999), has a scattered distribution and low percentage value (0.3-10%). This taxon is only found in the interval between 31m and 36m.
N. acostaensis, typical of cold and nutrient-rich waters (Bé 1977, Luz and Reiss 1983, Pujol and Vergnaud-Grazzini 1995), is discontinuously present with percentage abundance in the range of 0.6-100%, appearing at 13.60m and disappearing at 45m. Throughout the section, it is prevalently dextral, with occasional sinistral specimens.
Finally, G. scitula is almost always absent in the Gello Composite Section, with the exception of a short influx at 30m from the base, with peak of abundance of 60%.

Calcareous nannofossils

A qualitative and semiquantitative analysis was performed on calcareous nannofossil assemblages, which are scarce, moderately preserved and distributed discontinuously along the studied section.
Reworked Cretaceous (Arkhangelskiella cymbiformis, Biscutum sp, Eiffellithus sp., Ellipsagelosphaera sp., Ericsonia spp., Micula spp., Quadrum spp., Watznaueria barnesae), Paleogene and Miocene taxa (Cyclicargolithus abisectus, Dictyococcites bisectus, Sphenolithus heteromorphus, S. moriformis, S. radians) occur mainly in the lower part of the section. Messinian calcareous nannofossil assemblages appear at 12m from the base. They at first consist of common small reticulofenestrids and very rare discoasterids, whereas upward the assemblages are more diversified, including also taxa of the genus Amaurolithus, Coccolithus, Helicosphaera, Scyphosphaera, Sphenolithus and Umbilicosphaera.
The upper part of the section is characterized by a general decrease in specific diversity,

manifested by common oligotypical assemblages, which consist almost completely of Sphenolitus spp. and small specimens of Reticulofenestra and Dictyococcites, with occasional Amaurolithus, Discoaster and Helicosphaera.
Calcareous nannofossil are nearly absent in the uppermost part of the section, underlying the evaporitic gypsum.

Paleoenvironmental setting

The sedimentary features of the Gello Composite Section are indicative of a low-energy depositional area (i.e. below the wave base) characterized by decantation of fines with the recurrent establishment of anoxic bottom conditions (i.e the thinly-laminated marly clays) and the occasional emplacement of high density turbidity currents (i.e. the gravelly sand bed at about 26m from the base). Low oxygen bottom water is a common feature of several Mediterranean lower Messinian basins. Further constraints to unravel both the depositional setting and paleoenvironmental factors result from micropaleontological data. Indeed, it is well known that benthic foraminifera represent valuable paleoenvironmental tools, since they are substrate dependent and highly sensitive to several environmental factors (e.g., Wright 1978, Van der Zwaan 1982, Murray 1991). Most of the Gello Composite Section assemblages consist of taxa that are tolerant to high environmental stress, especially low oxygen content (e.g., Sen Gupta et al. 1989, Murray 1991). Particularly, B. echinata and B. dentellata are largely associated with hypersaline environments of the Mediterranean Messinian (Van der Zwaan 1982, Cita and Grignani 1983, Poignant and Moisette 1992, Violanti 1996, Kouwenhoven et al. 2006). The frequency of these taxa have been observed by many authors in studies of the Late Miocene Mediterranean (e.g. Di Napoli Alliata 1951, Di Napoli Alliata 1964, Salvatorini 1968, Van der Zwaan 1979, Cita and Podenzani 1980, Van der Zwaan 1982, Seidenkrantz et al. 2000, Goubert et al. 2001, Drinia et al. 2004).
Micropaleontological analyses allowed the subdivision of the succession in 4 intervals (text-fig. 9) with transitional boundaries, each one representative of peculiar paleoenvironmental conditions. The four intervals are described in stratigraphic order as follows:
Interval A (0-12m) - micropaleontological assemblages are dominated by ostracods, with subordinate benthic foraminifera, which show high frequencies (up to 90%) of Ammonia beccarii (with tepida form), B. echinata and B. spathulata are also present with rare and scattered occurrences. Calcareous plankton is very rare and appears at 12.07m from the base; it is represented by Orbulina spp. among foraminifera, small specimens of reticulofenestrids and discoasterids among the nannofossils. Remains of Echinoids firstly occur at 11.75m.
The paleontological content suggests this interval being deposited in a brackish marginal

setting. The transition to the overlying interval is gradual and occurs within an about 2m-thick horizon (12-14m) showing marine transitional conditions (text-fig. 9).
Interval B (14-24m) - micropaleontological assemblages are dominated by foraminifera with subordinate ostracods. Specific diversity is higher respect to the Interval A. Benthic foraminifera are abundant with high dominance of bolivinids (specifically B. spathulata, B. dentellata) and buliminids (specifically B. echinata) and Cassidulina spp., Rosalina spp., Cibicidoides pseudoungerianus, Elphidium spp. and others; agglutinateded taxa are rare. Planktonic foraminifera assemblages are characterized by high percentage of Turborotalita quinqueloba, T. multiloba, Neogloboquadrina acostaensis and orbulinids. Calcareous nannofossils are mainly represented by Dictyococcites spp., Reticulofenestra spp. (small specimens) and Sphenolithus spp.; furthermore, few specimens of Amaurolithus cf. amplificus, A. delicatus, A. cf. ninae, A. primus, Discoaster intercalaris, D. mendomobensis, D. neorectus, D. quinqueramus, Helicosphaera carteri, Scyphosphaera sp., Sphenolithus abies and Umbilicosphaera sibogae occur. A bloom of Scyphosphaera sp. is recorded at 22m, in the uppermost part of this interval
The presence of characteristic benthic foraminifera (B. echinata) indicates an oxygen-depleted environment at the bottom, with possible warmer superficial waters characterized by a higher salinity. This interval is referable to an inner-outer shelf setting.
Interval C (24-35m): benthic foraminifera assemblages are more diversified then in the lower intervals, although always dominated by bolivinids and buliminids. Moreover, high abundances of C. pseudoungerianus and agglutinants are recorded, whereas Cassidulina spp., Rosalina spp., H. bellincioni, M. soldanii, N. boueanum, V. bradyana and Elphidium spp. are occasionally present. In the lower part of this interval planktonic foraminifera are characterized by an increase in specific diversity, whereas calcareous nannofossils are rare (an increase of reworked pre-Neogene taxa is evident). In the upper part, the nannofossil assemblages acquire an oligotypic character, consisting almost completely of Dictyococcites spp., Reticulofenestra spp. (small-sized specimens) and Sphenolithus abies. However, sporadic and very rare specimens of A. delicatus, A. primus, D. quinqueramus, Helicosphaera cf. selli and Reticulofenestra rotaria occur.
On the whole, micropaleontological assemblages suggest an outer shelf setting with anomalous conditions of the water mass in terms of low oxygen content at the bottom and hypersalinity oscillations in the surface. Nevertheless, environmental conditions of this interval are less stressing respect to those of the previous interval.
Interval D (from 35m to the top): benthic foraminifera assemblages are dominated (up to 90%) by stress tolerant taxa (B. echinata, B. spathulata) and high values of V. bradyana. Planktonic foraminifera show a very low specific diversity and the assemblages are mainly represented by turborotalitids and orbulinids. Sinistral forms of N. acostaensis are common

in the lowermost part of this interval, whereas few dextral forms occur at the top. Calcareous nannofossils assemblages show a further decrease in specific diversity; since they are dominated only by Reticulofenestra spp. (small-sizedspecimens) and S. abies. Furthermore, few specimens of A. delicatus and H. cf. sellii are present. From 46.25 to 50 m high abundance of shallow-water benthic taxa (Elphidium spp., Rosalina spp.) occurs. The marked oligotypic character of the micropaleontological assemblages prevents the assessment of a reliable paleobathymetry and suggests highly stressed conditions with oxygen-depleted waters. This is also supported by the barren samples of the topmost part of the section, heralding evaporite deposition.

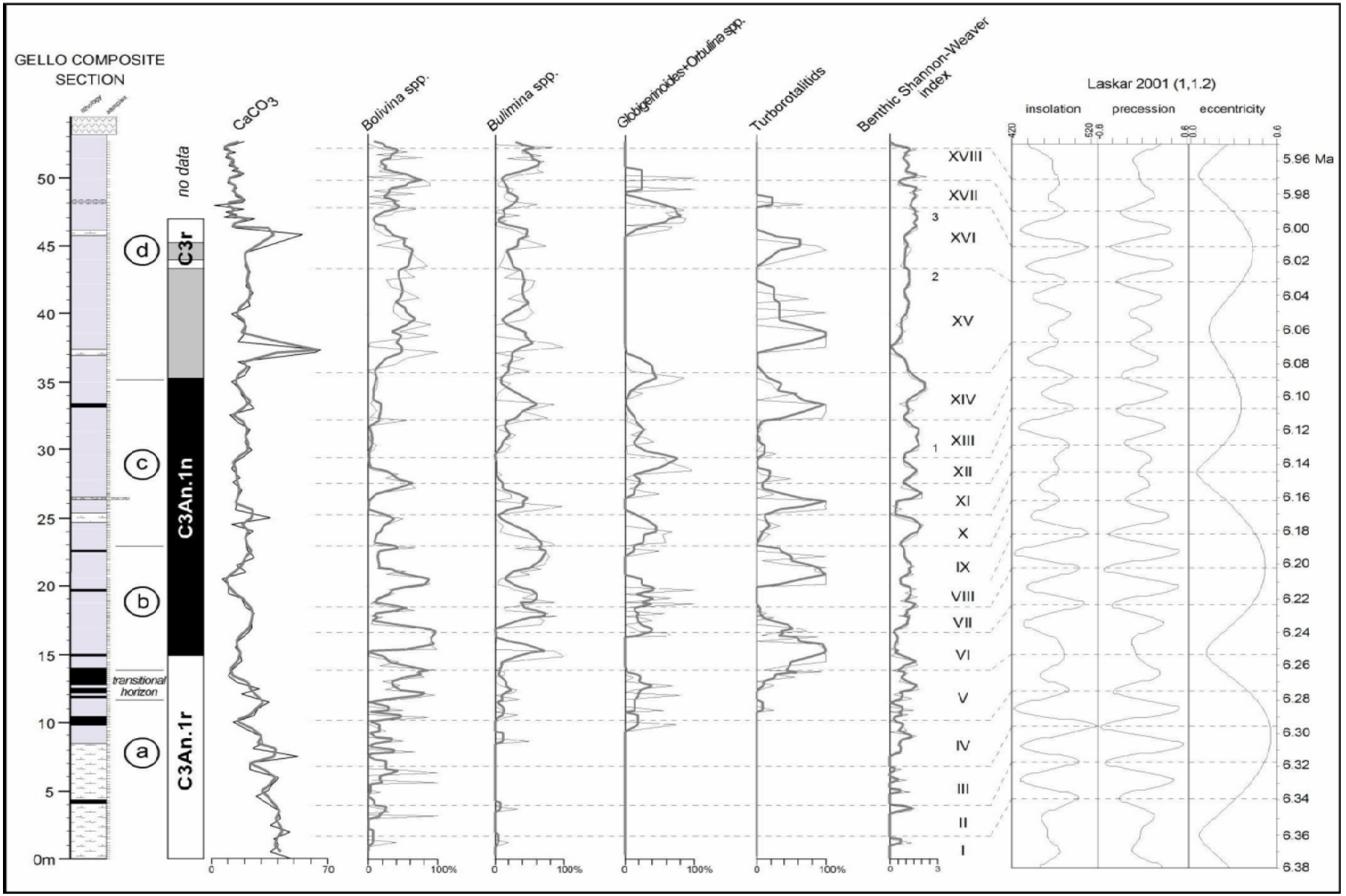
CYCLOSTRATIGRAPHY AND ASTRONOMICAL CALIBRATION

Rhythmic lithological alternations are commonly used to individuate depositional cyclicity and Milankovitch periodicities in the sedimentary successions. Cyclical lithological patterns are not present in the Gello Composite Section, thus different proxies showing cyclical patterns have been used. They are: $CaCO_3$ content (gasvolumetrically determinated) and faunistic fluctuations, all strongly related to climate changes. The magnetic susceptibility signal (measured by MS2 Magnetic Susceptibility System) has not yielded noticeably solutions. Taxa whose quantitative distribution curves show evident cyclical patterns (text-fig. 10) are: Bulimina spp., Bolivina spp. among benthic foraminifera, and Globigerinoides spp., Orbulina spp. and Turborotalita spp. amid planktonic foraminifera. Additionally, also the Shannon-Weaver index related to the benthic foraminifera exhibits rhythmic variations.

Significance of faunal proxies

The Bolivina group is composed of B. spathulata, B. dentellata and B. dilatata. The genus Bolivina is known to be very tolerant of low oxygen contents and typically characterizes Mediterranean sapropels. Herman (1981) observed that benthic foraminifera are generally absent within sapropelic deposits; when present, they consists of B. dilatata and specimens of Globobulimina. For example: i) Cita and Podenzani (1980) discovered an increase of Bolivina associated with the low-oxygen conditions that developed just prior to the deposition of the latest Pleistocene sapropel; ii) Ross and Kennett (1983/84) documented species of Bolivina in sapropels of Quaternary Sicily Strait, and iii) Katz and Thunell (1984) and Rio et al. (1997) documented B. catanensis and B. dilatata in most of sapropels from Sites 378 and 378A, and the Marecchia Valley section, respectively. Moreover, this genus has been constantly associated with Miocene and Pliocene laminites from the eastern Mediterranean Sea (Van der Zwaan 1983), and land sections (Capotondi Phd thesis).

The Bulimina group comprises B. echinata, B. elongata and B. costata. This group is


GELLO COMPOSITE SECTION
lithology
stratotypes
no data
CaCO3
Bolivina spp.
Bulimina spp.
Globigerinoides+Orbulina spp.
Turborotaliilids
Benthic Shannon-Weaver index
Laskar 2001 (1,1.2)
insolation
precession
eccentricity
420
520
0.6
0.6
0.6
d
c
b
a
C3r
C3An.1n
C3An.1r
transitional horizon
50
45
40
35
30
25
20
15
10
5
0m
0
70
0
100%
0
100%
0
100%
0
100%
0
3
XVIII
XVII
3
XVI
2
XV
XIV
XIII
1
XII
XI
X
IX
VIII
VII
VI
V
IV
III
II
I
5.96 Ma
5.98
6.00
6.02
6.04
6.06
6.08
6.10
6.12
6.14
6.16
6.18
6.20
6.22
6.24
6.26
6.28
6.30
6.32
6.34
6.36
6.38

usually the most abundant in the homogeneous intervals, and it is also reported as thriving under conditions of low oxygen and/or high organic matter supply (Sprovieri et al. 1996b, Rio et al. 1997, Sierro et al. 1999).

Generally, the benthic foraminifer assemblages are characterized by rapid shift in dominance and peaks of stress tolerant taxa (B. spathulata and B. echinata), as documented by Kouwenhoven et al. (2006) in the Pissouri Basin.

In the Composite Gello Section, the diversity of the benthic foraminifer assemblage as expressed by the Shannon-Weaver index ranges from 0 to 3. Sierro et al. (2003) and Pérez-Folgado et al. (2003) observed high abundance of benthic foraminifera in the homogeneous marls below the sapropels, while the planktonic foraminifera usually reach the highest values during sapropel deposition. Moreover, since sapropel deposition occurs under suboxic or anoxic bottom water, benthic foraminifera in these beds are low.

Globigerinoides spp. is represented by G. obliquus, G. extremus and G. cf. elongatus. It is known that the abundance fluctuations of these species reflect variations in sea surface temperature and their high percentages are related with warmer intervals and vice versa. Moreover, fluctuations of the Globigerinoides populations are controlled by Earth's orbital cycles (Sprovieri 1992, Sprovieri 1993, Sprovieri et al. 1996a, Sprovieri et al. 1996b, Caruso et al. 2002, Caruso 2004). Sprovieri et al. (1999), Bellanca et al. (2001) and Blanc-Valleron et al. (2002) observed in Falconara and Glibiscemi sections, high percentage of Globigerinoides spp. in the reddish and white laminites. In each homogeneous marly bed the relative abundance of this species decreases, with the lowest values generally in its middle part. In the Sorbas Basin Globigerinoides spp. together with Orbulina spp. show cyclical patterns and, moreover, are usually more abundant in the middle-upper part of the sapropels and within the sapropel and lower-middle part of the diatomites on Gavdos (Vàsquez et al. 2000, Sierro et al. 2001, Pérez-Folgado et al. 2003, Sierro et al. 2003).

Turborotalita spp. is represented by T. multiloba and T. quinqueloba. This group is characteristic of cold-eutrophic waters and is dominant in the homogeneous marls or at the transition between the homogeneous marls and the sapropel in the basins of the western Mediterranean (Sierro et al. 1999, Sierro et al. 2003). Accordingly, peaks of T. multiloba and T. quinqueloba usually occur at times of minimum diversity of planktonic foraminifera and low foraminiferal concentrations, thus suggesting that these intervals would have been

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Text-figure 10

Cartoon showing the tuning of the Gello Composite Section with the insolation, precession and eccentricity curves of Laskar 2001 (1,1.2) solution. Grey lines represent the tendency lines of selected taxa, diversity index and $CaCO_3$ curves.The main planktonic foraminiferal events are also shown - 1) second influx of Globorotalia scitula; 2) peaks in abundance of Turborotalita quinqueloba; 3) last peak in abundance of Orbulina spp.

characterized by stressing conditions. Bellanca et al. (2001) and Blanc-Valleron et al. (2002) documented high percentage of T. quinqueloba within the marls and in the topmost part of the diatomites of Tripoli Formation of the Sicilian Basin.
Generally, warmer planktonic foraminifer assemblages (Globigerinoides spp. and Orbulina spp.) are present in laminitic or sapropelitic levels, whereas colder ones (turborotalitids and neogloboquadrinids) are mainly present in the homogeneous levels.
According to Hilgen (1991) and Hilgen et al. (1995), the alternating sedimentation of sapropels (or laminitic beds) and homogeneous marl from throughout Mediterranean have an origin related to astronomical forcing; particularly individual sapropel corresponds to precession minima/insolation maxima, small-scale and large-scale sapropel cluster to 100 kyr and 400 kyr eccentricity maxima, while alternating thin-thick or present-absent ones reflect precession-obliquity interference (Hilgen et al. 1995).
Therefore, a close dependence between lithofacies and microfossil assemblages has been proved for sapropel-bearing successions, although by definition, the same microfossil assemblages can be considered as sensitive to astronomical periodicity also in successions lacking sapropels. Consequently, the abundance variations of the above-mentioned taxa, allowed the recognition of the astronomical precessional periodicity. Particularly, insolation maxima-precession minima correspond to: 1) minima in $CaCO_3$ content, in benthic Shannon-Weaver index, and in the distribution patterns of both Bulimina spp. and Turborotalita spp.; 2) maxima in the distribution pattern of both Bolivina spp. and Globigerinoides spp.-Orbulina spp.

Astronomically induced cyclicity in the Gello Composite Section
Since paleoenvironmental conditions changed repeatedly during deposition of the Gello Composite Section (see intervals A-D) and the presence of the above listed precession-insolation significant proxies are environment-dependent, each interval with peculiar paleoenvironmental conditions contains only a few of such proxies.
A precessional cycle is defined as the interval comprised between two precession minima (text-fig. 10). Accordingly, five precession cycles are present in the interval A plus transitional horizon (I-V). These cycles are highlighted by the distribution curve of Bolivina spp., which is in opposite phase with the curve of $CaCO_3$ content. The boundaries of cycles IV and V are also in correspondence with minima in the Shannon-Weaver index curve. Moreover, specific diversity of the first 3 cycles is very low and not significant. Similarly, curves of the planktonic taxa are not significant since this interval is related to a brackish setting.
Four cycles (VI-IX) have been documented in the interval B, mainly by the five abundance peaks of Bolivina spp. recorded between 13.86m and 22.87m. The distribution curve of Bolivina spp. is in opposite phase with that of Bulimina spp. and with Shannon-Weaver

index. Concerning the planktonic foraminifera distributions, the VII and VIII cycles are characterized by high percentages of Globigerinoides-Orbulina spp. just below the positive fluctuations of Bolivina spp.; while high abundance of turborotalitids are present in the VI, VII and IX cycles.
Interval C comprises five cycles (X-XIV). Specifically, cycles X and XI have been recognized by positive fluctuations of Bolivina spp. vs negative fluctuations of Bulimina spp., accompanied by minima in the curves of Turborotalita spp. and Shannon-Weaver index. In these cycles, the relative high abundances of Globigerinoides-Orbulina spp. come early the above mentioned proxies. Carbonate signal is not clear in cycles X and XI. Cycles XII and XIII, have been identified through the relationships between Bolivina spp.-Globigerinoides-Orbulina spp. maxima vs turborotalitids-benthic foraminifera diversity index minima. The last cycle (XIV) has been recognized by a relative high abundance of turborotalitids in correspondence to carbonate content-Bulimina spp. maxima. In this case, the positive fluctuations of Globigerinoides-Orbulina spp. occur in the upper part of the cycle.
Finally, four cycles (XV-XVIII) have been identified in the interval D. Specifically, cycles XV and XVI are highlighted by relation between Globigerinoides-Orbulina spp. maxima vs turborotalitids minima. The opposite trend of Bolivina spp. and Bulimina spp. is not clear in these cycles, whereas it marks the last two cycles (XVII and XVIII). Furthermore, Bolivina spp. maxima also correspond to minima in Shannon-Weaver index and in carbonate content curves.

Age constraints and Astronomical tuning

The astronomical tuning of the Gello Composite Section, as well as of any other section, requires age constraints in order to speculate on the nature of the recognized cyclical patterns. To this purpose, it is worth noting that i) the Gello Composite Section is younger than the age of the coiling change from sinistral to dextral of N. acostaensis (dated at 6.35 Ma: Lourens et al. 2004 and references therein) which represent the lower boundary of the MMi13 c Zone (Iaccarino et al. 2007) or Turborotalita quinqueloba Zone (Foresi et al. 2000/2001); and ii) the magnetostratigraphic boundary between C3An.1r and C3An.1n (dated at 6.252 Ma: Lourens et al. 2004 and references therein) is recorded at 14.77m. Moreover, the presence of reversal polarity samples (referred to the C3r) at the top of the section suggests the topmost section being younger than 6.033 Ma (age of the C3An1n/ C3r boundary in Lourens et al. 2004 and references therein).
Additional age constraints are represented by bioevents recorded in the studied section and occurring in others astronomically calibrated sections, such as the Abad Composite Section in Spain (Sierro et al. 1999, Sierro et al. 2001) and the Falconara Section in Sicily

(Sprovieri et al. 1996a, Sprovieri et al. 1996b, Hilgen and Krijgsman 1999, Blanc-Valleron et al. 2002), traditionally considered as the reference sections for Messinian pre-evaporitic cyclostratigraphical studies. Specifically, such bioevents are (biochronology from Lourens et al. 2004):
1) Peak in abundance of G. scitula - This species is almost completely absent in the studied section with the exception of a single short-lived incursion within cycle XIII in the middle-upper part of chron C3An.1n. This event (dated at 6.103 Ma) should correspond to that recorded within cycle UA 29 of the Upper Abad Composite Section.
2) Uppermost peak in abundance of T. quinqueloba - This species shows high percentage within cycle XV, just below the evaporitic deposition, where plankton is absent. The distribution curve of T. quinqueloba is correlate with that observed in the cycles UA 31 and T 46 of Abad Composite Section and Falconara Section, respectively. Cycle XV is interpreted as a double cycle, like Sierro et al. (2001) and Hilgen and Krijgsman (1999) do for their UA31 and T46 cycles.
3) Last peak in abundance of Orbulina spp. - This peak occurs in cycle XVI and it corresponds probably to that showed by cycle UA 32 of the Spanish section.

On the whole, the Gello Composite Section is well constrained by some chronohorizons and so it can be astronomically tuned with the Laskar 2001 (1,1.2) solution (text-fig. 10). The 18 recognized cycles, developed from 6.353 Ma (age of the base of the section) to 5.963 Ma (inferred age for the onset of gypsum deposition), represent the complete precession set of the recorded time interval. It is also undoubted that in the middle part of the section, the alternated major peaks in the distribution pattern of Globigerinoides spp./ Orbulina spp. and turborotalitids respectively, practically realize every two precession cycle and it testifies for an obliquity control on the developing of the planktonic assemblage.

CONCLUSIONS

A number of conclusions arise from the stratigraphic and cyclostratigraphic patterns recognized by means of a multidisciplinary study in the Messinian pre-evaporitic deposits of the Volterra Basin (Gello Composite Section). These conclusions are enumerated as follows:

1) The pre-evaporitic Gello Composite Section can be subdivided into four intervals, each one typified by peculiar paleoenvironmental conditions in terms of paleobathymetry and/or physico-chemical characters of the water. An overall deepening-upward trend characterizes the studied section, starting from the base up to its middle-upper part, when a decrease of water depth likely occurred, thus heralding the evaporitic deposition recorded

by the gypsum at the top of the section.
2) The combination of two major climate sensitive records, i.e. the fluctuations of $CaCO_3$ and faunistic contents (benthic and planktonic foraminifera), has highlighted the presence of 18 precession cycles and the influences of the lower frequency astronomical periodicities. Particularly, the distribution of the genus Bolivina and the Shannon-Weaver index curve are key records to unravel high frequency cyclicity, whereas the distribution of planktonic taxa seems to be controlled also by the obliquity periodicity.
3) The key bioevents characterizing some of the astronomically calibrated pre-evaporitic Messinian sections, such as Abad Composite and Falconara sections, have been recognized also in the Gello Composite Section. These bioevents along with the age of the C3An.1r/C3Ar.1n magnetostratigraphic boundary, have provided age constraints for the astronomical calibration of the section with the standard curves of the astronomical periodicity.
4) The beginning of the marine sedimentation in the Volterra basin aged at 6.255 Ma.
5) The pre-evaporitic marly sedimentation ended at 5.963 Ma. As a consequence, the onset of evaporitic phase related to the Messinian Salinity Crisis in the Volterra Basin and in others Mediterranean type-successions is isochronous.

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